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Sustainability Analysis of a Municipal Wastewater Treatment Plant through Emergy Evaluation

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Abstract: Water and wastewater treatment plants are essential for the supply of drinking water for consumption and the treatment of effluents produced by human/industrial activities. However, few studies deal with the investments and sustainability of these services, which consider both the contribution of nature and society. This study uses the emergy approach to evaluate a wastewater treatment plant located in the northeastern part of Romania, in Iași city. An assessment of the environmental costs of natural fluxes required for the treatment processes was performed, considering that the treated effluent is, still, loaded with contaminants that have to be absorbed by the receiving water natural system. The work done by nature to assimilate this load, generally considered free, is esteemed as a further cost in the total emergy budget of the wastewater treatment processes. The sustainability perspective was approached by calculating and analyzing the emergy yield ratio (EYR), environmental load rate (ELR), and emergy sustainability development index (ESI). The use of local renewable natural resources in Iași municipal wastewater treatment plants is negligible (1.71% of the total plant emergy budget), as compared to that of the purchased resources (98.29% of the total plant emergy budget) mainly processed with the support of fossil fuels' generated energy. The unit emegy value was, also, calculated and compared to other studies relevant for wastewater treatment plants. The analysis suggests that the large amount of emergy that wastewater contains is proportional to the number of resources employed for wastewater treatment and the extensive effects on surrounding ecosystems, where wastewater is discharged.

Keywords: wastewater treatment system; emergy analysis; sustainability

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1. Introduction

Water is a fundamental resource for development and the basis for humans and ecosystem functioning, and it is the reason why, in the urban water cycle (comprising the water supply as well as wastewater collection and treatment systems), decisions should be made by considering more accurate and systemic approaches based on economic, social, and environmental criteria. In this context, municipal wastewater treatment plants (MWWTP) are designed to improve wastewater quality, for discharge into the river bodies or for recycling/reuse for other activities (irrigation, aquifer recharge, municipal or industrial use). Nevertheless, this activity requires extensive material and energy consumption that has environmental impacts on different scales, although, in their absence, these impacts would be higher [1,2]. One of the main problems that needs a solution and feedback from society is how to replace the freshwater resources and to minimize the environmental impacts associated with wastewater treatment and discharges.

Currently, the wastewater discharges and water quality are of local and global interest, driven by legislation in force (for example, Water Framework Directive and Wastewater

Directives in Europe). Different monitoring techniques have been developed for both water and wastewater monitoring, such as conventional techniques (laboratory analyzes), mathematical modeling [3], and different types of sensors (satellite and in-situ sensors) [4], which bring improvements to water quality surveys and ecosystems preservation. The introduction of quality sensors in the sewer systems, to detect various pollutants, may contribute to their adequate functioning and of the MWWTP, reducing, thus, the impacts on the receiving water bodies, especially in the case of combined sewer overflows [5]. Although important, all these techniques focus on small-scale processes and do not take into consideration the broader window needed when discussing sustainability issues.

In recent years, many studies aimed to develop and use environmental management instruments to conceptualize and quantify human activities' direct and indirect effects on the environment, to enable decision-makers to track and measure progress towards sustainability goals and outcomes. These environmental management instruments include the Ecological Footprint [6,7], Cost-Benefit Analysis [8], Energy Flow Analysis [9], Exergy Analysis [8,10], Life Cycle Assessment (LCA) [11–14], Integrated assessments [15,16], and Emergy Analysis [1,8,17–20]. However, a method that is suitable from the sustainable development perspective has to consider all interactions between environmental, social, and economic impacts of wastewater treatment systems. Consequently, some methods are unable to provide a holistic approach and a unified measurement for sustainability evaluation, so it is the Emergy Analysis (EmA) that comes to accomplish such concerns.

EmA was introduced for the first time by Odum [17] and is defined as the total amount of available energy (exergy) used, directly and indirectly, which is needed to obtain a product or service. According to Odum [17], the solar energy represents the driving force for the other forms of energy and can quantify and hierarchize them in a common unit of measure, solar emergy joules (sej). As a valuable tool for environmental impact assessment and decision-making [21], EmA has been used in various sectors of economy, such as agriculture [22], industry [9,23,24], and urban systems [25], as well as for power generation [26], goods production [26,27], and waste treatment [28].

Examples of using EmA to assess wastewater treatment systems are available in the literature. For example, Giannetti et al. [1] analyzed two different wastewater treatment systems commonly used in Brazil. By comparing two different domestic wastewater treatments (conventional and biodigestion), these authors analyzed the consumption of energy and materials as well as the ecosystem's services required to deal with the carbon emissions of both systems. Grönlund et al. [29] performed an EmA for a wastewater treatment pond system, to assess sustainability of wastewater sludge management. Vassallo et al. [30] took into consideration the environmental costs of natural fluxes of a wastewater treatment plant, while Arden et al. [19] quantified the total resources used by an urban water system, from raw water extraction to wastewater discharge. Other authors, Siracusa and La Rosa [31], proposed the construction of a wetland on a Sicilian wastewater treatment plant's site, to provide the option of recycling treated water, reducing the pressure on the local environment, and reducing electricity consumption (which resulted in savings). Cano Londoño et al. [32] established an emergy-based methodology, for comparing two biosolids management alternatives. The common findings of these studies are related to the idea that, after wastewater treatment, the effluent discharged has a limited number of contaminants, according to the legal requirements. However, this study goes further, accounting for the environmental services required to assimilate and dilute pollutants, after the effluent is released into the natural environment.

In terms of sustainability, the relationship between wastewater treatment systems and the environment has become a topic of interest for researchers. Shao et al. [18] created improved evaluation indicators based on emergy theory, to compare four different wastewater treatment processes from a sustainability perspective. The study provides guidance for policymakers, on choosing a wastewater treatment technology for a new plant or upgrading for existing plants. Zhang et al. [33] proposed two alternative scenarios for a sewage treatment system, based on improved emergy indicators. The results obtained suggest that the treated wastewater and sewage-sludge reuse can further improve the environmental benefits of the treatment process. Grönlund [8] applied five methods, i.e., LCA, Exergy Analysis (ExA), EmA, Cost Benefit Analysis (CBA), and Environmental Risk Assessment (ERA), for assessing wastewater-sludge sustainability. He concluded that no method could cover every aspect, from a sustainability point of view, and suggested a complementary and integrated approach of methods and indicators to assess sustainability. Additionally, through geoinformatics tools, Fonseca et al. [34] facilitated emergy accounting for allocating water resources to domestic, industrial, and agricultural uses. These studies used, in different manners, the emergy theory to assess the sustainability of the wastewater treatment plants, based on the idea that a holistic approach is needed.

Until now, several studies in the wastewater treatment field have applied the EmA as an environmental performance assessment tool. As a result of the literature review, examples of EmA application in the field of wastewater-treatment systems are summarized in Table 1.

Table 1. EmA application in the field of wastewater treatment systems.

Refs	Application of EmA	Country
[35]	Municipal wastewater treatment and generation of electricity by digestion of sewage sludge.	Sweden
[36]	Analysis and comparison of the use of environmental resources in three different wastewater treatment systems: conventional MWWTP, MWWTP coupled with constructed wetland; and treatment in a natural wetland.	Sweden
[31]	Evaluation of the use of environmental resources for a conventional treatment plant, coupled with a constructed wetland.	Italy
[30]	Evaluation of the complete treatment for an MWWTP.	Italy
[33]	Improved emergy-based indicators applied to evaluate two alternative scenarios for a sewage treatment system.	China
[1]	Analysis of two different wastewater treatment systems commonly used in Brazil, calculating the role of energy and materials consumption and carbon emissions.	Brazil
[18]	Comparison of four different wastewater treatment processes from a sustainability point of view.	China
[37]	Assessment of the environmental economic value and sustainability of a decentralized sewage treatment plant.	China
[32]	Sustainable utilization of biosolids generated in a municipal wastewater treatment plant.	USA
[34]	Scenarios for transition from water supply of an overexploited aquifer to wastewater treatment plants that are capable of implementing additional units to achieve drinking water quality.	Mexico
[29]	Emergy assessment of a wastewater treatment pond system.	Sweden
[19]	Provided a quantification of the total resource use of an urban water system, from raw water extraction for drinking water to wastewater treatment and discharge.	USA
[8]	Explored the sustainability of wastewater and sludge management from a systems ecological perspective.	Sweden

The contribution of this work is the inclusion of the environmental services needed to reduce the concentration of the main contaminants of the treated effluent. The EmA method was improved, in order to cover and refine wastewater treatment, from a sustainability indicators point of view. In this way, a complementary and integrated approach to assess sustainability is considered, by including the work provided by the ecosystems services, in finalizing or completing the treatment provided by the MWWTP.

This study objective is to assesses the environmental performance of the Iași MWWTP, situated in the northeastern part of Romania, by using the EmA as performance assessment tool. To fulfill this objective, the following research steps are proposed: (1) accounting for all emergy inputs into the system and examining the requirements of environmental resources for wastewater treatment; (2) accounting for the environmental services required for assimilating and diluting pollutants, after the effluent is released from the plant; (3) calculating and analyzing the sustainability related indicators: emergy yield ratio (EYR), environmental load rate (ELR), and emergy sustainability development index (ESI); and (4) providing a comparison with other relevant research, based on the methodological approach and the unit emergy value of treated effluent.

This study represents a premiere in Romania, contributes to the sustainability assessment from a holistic point of view, provides a methodological comparison with other assessment studies, and supports a sustainable wastewater management that considers the extra work, performed by natural systems, to obtain water that is free from anthropogenic contaminants. The Iași MWWTP operates in a way that is similar to the majority of plants in Romania and in other countries, and the method applied in this work can be reproduced to assess and can improve the wastewater treatment system, at a national and international scale. Moreover, this plant's environmental performances were evaluated in other studies by means of life-cycle assessment as well aswater footprint, environmental impact, and risk assessment, thus motivating its selection as a case study.

The structure of this article is as follows: after the introduction section, Section 2 describes the methodology of EmA and impacts of the discharged pollutants on the environment (river). Section 3 presents the process flow sheet and operating conditions of the MWWTP chosen for analysis. Section 4 presents the results, including emergy flow diagram, emergy calculating tables, and graphics. Section 5 is dedicated to discussion based on emergy indicators, and the conclusions are summarized in Section 6.

2. Methodology

2.1. Emergy Analysis (EmA)

EmA is an environmental accounting method used to quantify all inputs (resources, goods, or services) to build and maintain any system, including municipal wastewater treatment systems [1,19]. To do so, an energy system diagram was drawn, by using the appropriate symbols developed by Odum [17]. The energy diagram shows the mass and energy flows, their interaction, and the boundary of analysis. All of an evaluated system's inputs are represented, from left to right along the diagram, according to a decreasing renewability rate. To convert them to emergy units, they are multiplyied by a conversion factor named transformity (Unit Emergy Value—UEV), which is the emergy amount required to obtain a Joule of a product or service (sej/J). The relationship between the emergy of an input flow i (Em_i) and its energy content (E_i) is given by its transformity (Tr_i) [17]:

$$Tr_i = Em_i / E_i \tag{1}$$

The total emergy, Y, supporting a system or a process, is calculated according to the following equation [17]:

$$Y = \sum_{i=1}^{n} f_i \times UEV_i \tag{2}$$

where f_i is the ith input flow (material, energy, or currency) and the ith UEV_i of the flow (adapted from the literature or calculated).

Wastewater is the primary input into MWWTP, together with auxiliary inputs from natural and social resources, while the main outputs are the treated wastewater and sludge. In our study, the system boundary included the entry into the reception chamber of the raw wastewater, until this was returned into the environment as treated effluent and digested sludge. Among the natural inputs, the oxygen demand of the aerobic decomposition phases of organic matter and nutrients was included in the calculation.

The emergy flows of the evaluated system are classified according to their categories, in renewable (R, inputs obtained "free" from nature) and non-renewable (N) resources as well as purchased resources (F, those that were either purchased or processed) from the economic sector. An association of their percentages resulted in the emergy indices, which offer a better understanding of the system's environmental performance regarding the resources used [1]. The framework methodology of EmA is represented in Figure 1.

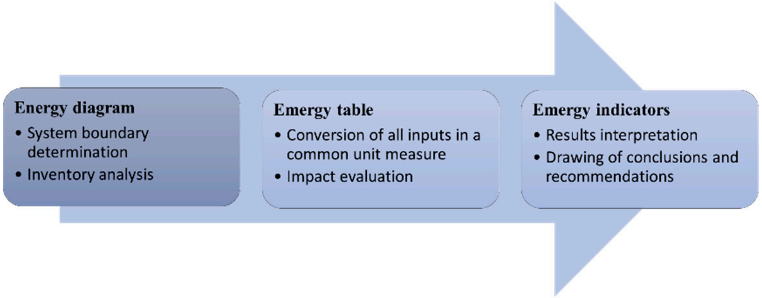

Figure 1. Framework methodology of EmA (adapted after [18]).

The system diagram was the first step in the analysis of EmA and, based on it, the construction of the energy evaluation table followed. Thereby, the raw data of inputs (materials, energy, labor, and services) were grouped and converted into emergy units, by multiplying them with the corresponding transformity. The foreground data included in our analysis were provided directly by the Iași MWWTP operator and extracted from documents, such as activity reports and environmental permits. However, because of the "age" of the wastewater treatment plant, the lifespan of buildings and machinery was estimated to be 50 years and 20 years, respectively, and, referring to the materials needed for construction, only iron, concrete, gravel, bricks, and asphalt were considered. From the total amount of materials, 3% was estimated for maintenance works. Among renewable resources, only wind, which gives the most significant emergy contribution in the present analyses, has been included in the total. In contrast, the others were calculated and, then, excluded from the total emergy value, to avoid double counting. For all inputs of the studied system, transformities (UEVs) were obtained from the literature. In this study, all UEVs used, calculated, and cited, hereafter, are referenced by the 12.0×10^{24} sej/year global emergy baseline [38].

Like other environmental assessment methods, EmA is based on mathematical rules, known as emergy algebra rules [39]:

Rule 1: According to the emergy definition, the emergy of output is given by the sum of all inputs, multiplied by their transformities;

Rule 2: Co-products resulting from a process contain all emergy used in the process;

Rule 3: When a pathway splits, this means that the amount of emergy assigned to each path depends on the percentage of energy that flows through that path;

Rule 4: Emergy cannot be counted twice within a system, when: (a) emergy flows are feedback; (b) co-products are reunited; and (c) used resources involve financial transactions.

A methodological comparison, with other environmental assessments of this MWWTP, presented by Teodosiu et al. [2], was completed with the main aspects of emergy analysis shown in this study and is depicted in Table 2.

Table 2. Environmental assessment methods comparison.

Method	**Life Cycle Assessment (LCA)**	**Environmental Impact Quantification (EIQ)**	**Grey Water Footprint (GWF)**	**Emergy Analysis (EmA)**
Impact quantification principle	Causality chain (emission, transport, effect, damage)	Individual polluter contribution to river pollution (load)	Virtual water volume needed to dilute pollution to acceptable levels	Holistic evaluation of a process sustainability
Impact definition (meaning)	Impact (damage) = Magnitude × dose × exposure	Impact = magnitude (loads) × severity (receiving river status)	Impact = virtual water volume needed to dilute pollutant loads to acceptable levels	Impact = resources, goods, or services consumption, to build and maintain the wastewater treatment system
Impact Classification System (reference system)	• Characterization factors and reference substance (impact), within a specific impact category	• River natural water quality (spring section) • River water quality upstream of the discharge point	River natural water quality (spring section)	Emergy required of the process, to produce 1 Joule of a product or service
Data requirements	Emissions to air, water (quality indicators) Waste flows Wastewater flows Electricity use Natural gas consumption Materials use	Wastewater quality indicators Water quality indicators Wastewater Flows	Wastewater quality indicators Water quality indicatorsFlows	Energy flows (sunlight, wind, etc.) Electricity, fuels, and chemicals consumption Production materials Human labor and services Machinery and equipment Water and wastewater flows Financial resources
Strong points	• Generation of complex environmental profiles • Comparison among different impact categories and different environmental components • Technical and economical performance evaluation tool	• Characterization of local impacts • Characterization of individual pollution contributions • Consideration of legislative frameworks • Rapid assessment • Versatility and Adaptability • May be applied by WWTP or water authority specialists (provided with an established methodology)	• Characterization of local impacts • Characterization of individual pollution contributions • Consideration of legislative frameworks • Rapid assessment • Versatility • May be applied by WWTP or water authority specialists (provided with an established methodology)	• Characterization of local impacts • Converting all flows into a common unit • Donor-side assessment method • Widely used for a variety of systems

Table 2. *Cont.*

Method	Life Cycle Assessment (LCA)	Environmental Impact Quantification (EIQ)	Grey Water Footprint (GWF)	Emergy Analysis (EmA)
Weak points	• Complex data requirements • Inconsistent impacts definition in LCIA methods • Rigid assessment framework • No correlation to local conditions or legislative requirements • May be applied only by LCA specialists	• Method sensitivity depends on data quality (no. of water quality samples) • The environmental profile is limited to the water component	• Method sensitivity depends on data quality (no. of water quality samples and no. of indicators) • The environmental profile is limited to the water component	• Complex data requirements • Accuracy problems • Standardization issues • May be applied by specialists
Development status and integration	• Well developed for MFA and product systems • In development for water systems and improved water-related impacts (international standard development)	• Initial development	• Well developed for product systems • In development for WWTP assessment	• Well developed for macroscopic and microscopic systems

It may be observed from this table, that although there are some common methodological issues, such as a holistic approach, complex data requirements, and the necessity to be applied by specialists (EmA and LCA), the characterization of the local impacts is better presented by EIQ, GWF, and EmA. All the methods are well developed for wastewater treatment systems and may be integrated with other assessment instruments (especially LCA and EmA).

2.2. *Environmental Impact Emergy of Pollutants in Treated Wastewater Discharges*

Usually, the treatment efficiency of a municipal wastewater plant is established by its capability to remove/reduce the organic matter and nutrients loads in wastewater. All the pollutants concentrations discharged in the Bahlui River must meet the national standards (in terms of COD, BOD, TSS, TN, and TP), standards that are transposing the relevant EU legislation [40]. Even if some pollutants may be found in small amounts in the treated wastewater and environment, they should be considered in emergy calculations. The impact of discharged contaminants on the environment can be calculated based on the emergy associated with diluting these pollutants, considering their concentrations in the river (Table 3). The water required for diluting the pollutants can be calculated with the following formula [18]:

$$M_{w,i} = d \times \left(\frac{W_i}{c_i}\right) - M_w \quad (3)$$

where, $M_{w,i}$ means the water necessary for pollutants dilution expressed in g, d is the density of water equal with 1×10^6 g/m^3, W_i means the quantity of pollutant i discharged expressed in g, c_i is the pollutant i concentration in effluent expressed in g/m^3, and M_w means the total quantity of the wastewater treated discharged expressed in g. These calculations adopted the actual concentrations of different pollutants in the river (effluent values—Table 3). To calculate the emergy associated with water requirement for diluting pollutants, the following formula was used [18]:

$$ECEW_i = M_{w,i} \times 4.92 \text{ J/g} \times 4.48 \times 10^4 \text{ sej/J} \quad (4)$$

where, $ECEW_i$ means the emergy required for diluting the water pollutant i (expressed in sej), the number 4.92 J/g is the Gibbs free energy of water, and the number 4.48 × 10^4 sej/J is the emergy transformity of surface water [18].

Table 3. General parameters for the Iași municipal wastewater treatment plant.

Parameter	Value
Year of inventory	2019
Year plant was built	1968
Number of people served	386,000
Area of plant	~14 ha
Assumed lifetime of building, tanks, and pipes	50 years
Assumed lifetime of machinery	20 years
Treated wastewater volume	44,919,743 m^3/year
Sludge volume	12,000 m^3/day
Electricity consumption	9542.015 MWh/year

3. MWWTP Description

The Municipal Wastewater Treatment Plant is located in Dancu, Iași city, and is operated by a regional water company (SC APAVITAL SA), with responsibilities for the water supply and wastewater management (collection, treatment, discharge) for more than 880,000 people at the county level, including 386,000 inhabitants of Iași and the boundary area [2]. More than 95% of the population served by this regional operator is connected to water and wastewater services [41].

The Iași MWWTP was developed in stages, since 1968 [41]. In 2015, the wastewater treatment lines were fully refurbished and upgraded, to reach an increased capacity: from 190,000 m^3/day and 37,300 kg BOD/day to a maximum flow of 280,000 m^3/day and 56,000 kg BOD/day [42]. A tertiary treatment (comprising nitrogen and phosphorous removal) was implemented, with the purpose to prevent eutrophication of the surface water, where the wastewater is discharged, or to facilitate wastewater recycling [12,41].

All wastewater collected from Iași city is treated at the Iași MWWTP (mechanically, biologically, and chemically) and, then, is discharged into the Bahlui River, complying with NTPA 001/2005 [40]. The main parameters for the Iași MWWTP are presented in Table 3, to facilitate the EmA.

The wastewater treated by the Iași MWWTP follows the process flow, presented in Figure 2, and consists of the following treatment stages [2,42]:

- **the mechanical stage** includes pumping stations, fine and coarse screens, a fat separator, grit removal, and primary sedimentation, and is where the suspended solids and a small part of the organic load are retained;
- **the biological stage** includes the conventional activated sludge and nitrification/denitrification processes, followed by secondary sedimentation, and is where carbon-based biodegradable compounds and nutrients (nitrogen and phosphorus compounds) are removed;
- **the chemical stage** includes phosphorus removal using ferric chloride ($FeCl_3$), in three different points of the process flow.

Over the years, the Iași MWWTP has greatly improved its efficiency, reaching an essential step in aligning with the EU's environmental quality and safety standards. The good efficiency of the MWWTP is proven by the values presented in Table 4, for the significant wastewater quality indicators. The removal efficiency (RE) was calculated with the following equation [15]:

$$RE = \frac{C_i - C_f}{C_i} \times 100\% \tag{5}$$

where: RE is the removal efficiency, (%); C_i and C_f arethe pollutant concentrations (mg/L) in the influent and effluent, respectively, for each wastewater-quality indicator detailed in Table 4.

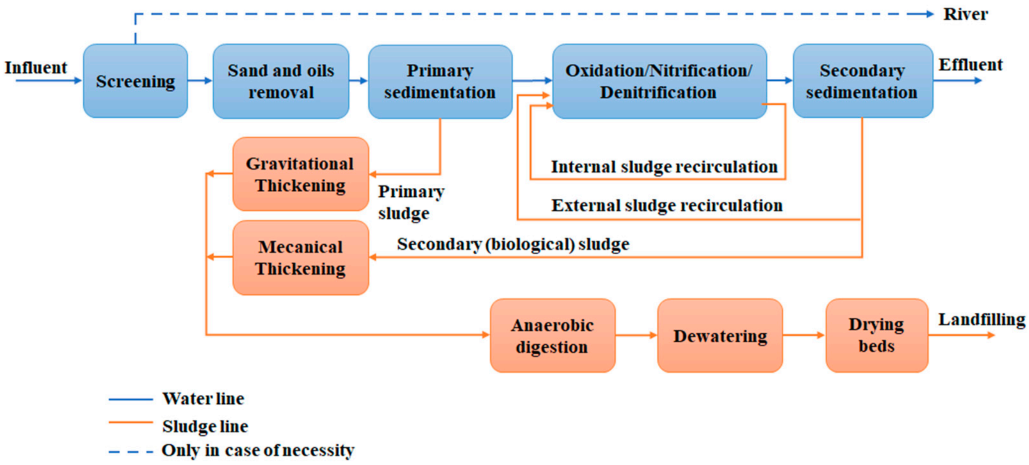

Figure 2. The Iași MWWTP flow-sheet (source: APAVITAL).

Table 4. Efficiency removal indicators between the influent and effluent of the Iași MWWTP, in 2019.

Wastewater Quality Indicators	Influent Values (mg/L)	Effluent Values (mg/L)	MAC * (mg/L)	RE, %
Biochemical oxygen demand, BOD	139.90	9.44	25	93.25
Chemical oxygen demand, COD	228.50	30.96	125	86.45
Total suspended solids, TSS	141.93	10.39	35	96.28
Total Nitrogen, TN	29.55	6.76	10	77.14
Total Phosphorous, TP	3.43	0.91	1	73.50

* MAC = maximum acceptable concentration for discharge in water bodies, according to NTPA 001/2005 [40].

These wastewater quality indicators were considered because they are the most representative of the design and operation of MWWTP.

4. Results

The energy system diagram of the Iași MWWTP, managed by the regional water operator SC APAVITAL SA (Figure 3), was drawn by using the appropriate symbols developed by Odum [17]. The system depends on natural 'free' resources, such as solar radiation, rainfall, wind, and atmospheric oxygen, and paid resources from the larger economy (where money circulates; the dashed line is related to services), including chemicals, fuels, electricity, machinery, and human labor. All these external resources interact through internal processes (pump station, bar and screens, grit and grease removal, primary sedimentation, and so on), generating heat that is recirculated, electricity to the grid, sludge that is transported to landfills, and treated water released to the Bahlui River.

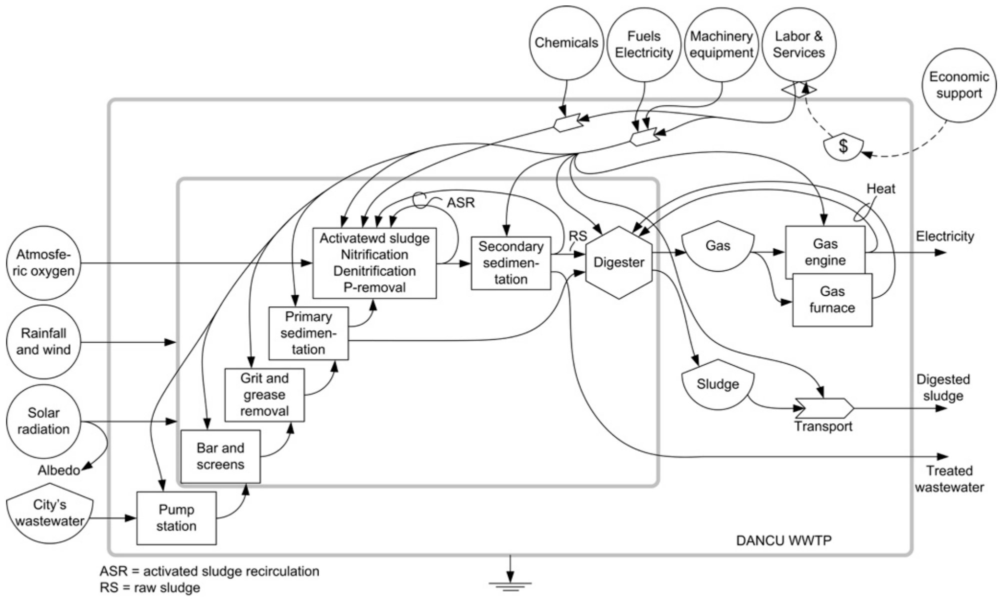

Figure 3. The Iași MWWTP's energy-flow diagram. The $ sign stands for the economic support needed for labor and services.

The algebraic sum of all the represented fluxes, counting renewable, non-renewable, and purchased resources, results in the total emergy required to treat the wastewater.

EmA of the Iași MWWTP activity was performed, with data from 2019. Results are reported in Table 5 and illustrated in Figure 4.

Table 5. EmA table for the Iași MWWTP.

Item	Unit	Basic Data (unit/yr)	UEVs [(b)] (sej/unit)	Refs.	Emergy (sej/yr)	Percentage %	Unit Ton of Emergy
			Renewable resources—R				
Sunlight [(a)]	J	6.62×10^{14}	1	[17]	6.62×10^{14}	0.00%	1.47×10^{7}
Wind, kinetic energy	J	2.71×10^{13}	8.00×10^{2}	[19]	2.17×10^{16}	<1%	4.83×10^{8}
Rain, chemical energy [(a)]	J	3.86×10^{11}	7.00×10^{3}	[19]	2.70×10^{15}	0.00%	6.02×10^{7}
Rain, potential energy [(a)]	J	1.54×10^{9}	2.79×10^{4}	[43]	4.30×10^{13}	0.00%	9.57×10^{5}
Oxygen	g	5.86×10^{9}	6.56×10^{7}	[44]	3.84×10^{17}	1.61%	8.56×10^{9}
			Non-renewable resources—N				
Land occupation	m^2	1.40×10^{5}	1.27×10^{9}	[19]	1.78×10^{14}	0.00%	3.96×10^{6}
			Purchased resources—F				
Human labor	J	2.84×10^{11}	1.36×10^{7}	[43]	3.86×10^{18}	16.23%	8.60×10^{10}
Electricity	kWh	9.54×10^{6}	7.94×10^{11}	[17]	7.58×10^{18}	31.83%	1.69×10^{11}
Fuels (gasoline)	J	4.84×10^{12}	1.74×10^{5}	[19]	8.42×10^{17}	3.54%	1.87×10^{10}
Fuels (oil)	J	4.27×10^{9}	1.23×10^{5}	[19]	5.25×10^{14}	0.00%	1.17×10^{7}
Ferric chloride	kg	864,600	4.87×10^{12}	[44]	4.21×10^{18}	17.69%	9.37×10^{10}
Polyelectrolyte	kg	4860	4.51×10^{12}	[19]	2.19×10^{16}	<1%	4.88×10^{8}
Iron	kg	8.76×10^{5}	3.07×10^{12}	[19]	2.69×10^{18}	11.30%	5.99×10^{10}
Concrete	kg	1.35×10^{6}	1.93×10^{12}	[43]	2.61×10^{18}	10.96%	5.81×10^{10}
Gravel	kg	4.06×10^{3}	1.42×10^{12}	[43]	5.77×10^{15}	<1%	1.28×10^{8}
Brick	kg	4.26×10^{4}	2.82×10^{12}	[43]	1.20×10^{17}	<1%	2.67×10^{9}
Asphalt	kg	4.14×10^{5}	3.49×10^{12}	[43]	1.44×10^{18}	6.07%	3.22×10^{10}
Maintenance	kg	4.03×10^{6}	3.37×10^{9}	[35]	1.36×10^{15}	<1%	3.03×10^{8}

Table 5. *Cont.*

Item	Unit	Basic Data (unit/yr)	UEVs [(b)] (sej/unit)	Refs.	Emergy (sej/yr)	Percentage %	Unit Ton of Emergy
Emergy value of renewable inputs, R					4.06×10^{17}	1.71%	9.06×10^{9}
Emergy value of non-renewable, N					1.78×10^{14}	0.00%	3.96×10^{6}
Emergy value of purchased inputs, F					2.34×10^{19}	98.29%	5.21×10^{11}
Emergy value used for wastewater treatment, Y					2.38×10^{19}	100.00%	5.30×10^{11}
Total emergy, without environmental services						2.380×10^{19}	
Emergy per unit of treated wastewater (transformities calculation)							
Emergy per m^3 of treated wastewater			sej/m^3			5.30×10^{11}	
Emergy per J of treated wastewater			sej/J			12.4	
Emergy per g of treated wastewater			sej/g			5.30×10^{5}	

Notes: the table presents the values with accuracy to two decimal places, but they are fully included in the emergy calculation. Each of the items' amounts were computed, using information received from the MWWTP. In this case, the total emergy result was equal to 2.38×10^{19} sej/year, and, to treat one ton of wastewater in the urban area of Iași city, the plant requires 5.30×10^{11} sej/year. $ECEW_{max}$ was selected as the maximum emergy value of a particular pollutant, as the representative value of all pollutants in the sewage system. [(a)] The sum of renewable natural resources emergy R was derived from the maximum emergy value of wind, rain, and sunlight items, to avoid double counting [17]; [(b)] Unit Emergy Values (UEVs) refer to the 12.0×10^{24} sej/year baseline [38].

1. **Sunlight** = area of the plant (m^2) × average solar radiation of the city, J/m^2/year

Area of the plant = 14 ha = 14,000 m^2; average solar radiation is a climatic parameter and it was taken from [45].

2. **Wind, kinetic energy** = area of the plant × air density × drag coefficient × geostrophic wind^3 × (3.154×10^7)

Area of the plant = 14 ha = 14,000 m^2; air density = 1.23 kg/m^3; drag coefficient = 0.03; 3.154×10^7 s in year; and geostrophic wind = average wind speed $\times 10^6$.
Average wind speed is a climatic parameter (m/s), and it was taken from [46].

3. **Rain, chemical energy** = area of the plant × average rainfall × water density × Gibbs free energy of water

Average rainfall (m/year) is a climatic parameter, and it was taken from [46].
Area of the plant = 14 ha = 14,000 m^2; water density = 1000 kg/m^3; and Gibbs free energy of water = 4.94×10^3 J/kg.

4. **Rain, potential energy** = area of the plant × average rainfall × elevation × runoff rate × water density × gravity

Area of the plant = 14 ha = 14,000 m^2; water density = 1000 kg/m^3; Gibbs free energy of water = 4.94×10^3 J/kg; runoff rate = 20%; elevation = 10 m; and gravity = 9.81 m/s^2.
Average rainfall (m/year) is a climatic parameter, and it was taken from [46].
The elevation of the plant was taken from the environmental permit of APAVITAL SA.

5. **Land occupation** = area of the plant = 14 ha = 14,000 m^2, taken from Environmental Permit of APAVITAL SA
6. **Human labor** = average quantity × number of workers × daily requirement of human metabolism [1]

Average quantity = 365 days/year, 24 h/day; number of workers = 62; and daily requirement of human metabolism = 3000 kcal/day for men × 4186 J/kcal.

7. **Oxygen** (aerobic decomposition) = (BODin − BODout) × treated water/year

BODin, g/L = 0.14; BODout, g/L = 0.0095; and treated water, L/year = 4.49×10^{10}.

8. **Electricity** (entire WWTP) = electricity consumption, kWh

Electricity consumption = 9,542,015 kWh, taken from the environmental permit of APAVITAL SA.

9. **Fuels (gasoline)** = volume consumed × conversion J/m^3

   Volume consumed = 113,400 L/year; and J/m^3 conversion = 4.27×10^{10} J/m^3, [29].
   Fuels (oil) = volume consumed × conversion J/m^3.
   Volume consumed = 100 L/year; and J/m^3 conversion = 4.27×10^{10} J/m^3, [29].

10. **Ferric chloride** (P-precipitation) = 864,600 kg/year, from the environmental permit of APAVITAL SA

11. **Polyelectrolyte** (sludge dewatering) = 4860 kg/year, from the environmental permit of APAVITAL SA

12. **Buildings materials** amount, divided by plant lifespan

Iron = 4.38×10^7 kg; concrete = 6.76×10^7 kg; gravel = 2.03×10^5 kg; brick = 2.13×10^6 kg; asphalt = 2.07×10^7 kg; and plant lifetime = 50 years.

13. Maintenance works were estimated to be 3% of the total amount of materials in the buildings and machinery [19].

Treated wastewater outputs may contain different types of pollutants. To characterize the performance of the Iași MWWTP, five water quality indicators (with relevance to the design and operation of MWWTPs) were selected: chemical oxygen demand (COD), biological oxygen demand (BOD), total suspended solids (TSS), total nitrogen (TN), and total phosphorus (TP). The ECEW values of wastewater pollutants were calculated, according to Equations (3) and (4) as well as Table 4. The maximum emergy value ($ECEW_{max}$) of a particular pollutant was considered in the analysis as the representative value of all pollutants in the sewage system (Table 6) and can be associated with the amount of resources that must be employed after the wastewater treatment, to mitigate effects on surrounding ecosystems, where the treated wastewater is discharged.

Table 6. Environmental impact emergy of pollutants in the treated wastewater discharge.

1	$ECEW_{BOD}$	2.31×10^{16} sej/year
2	$ECEW_{COD}$	7.95×10^{15} sej/year
3	$ECEW_{TSS}$	2.57×10^{16} sej/year
4	$ECEW_{TN}$	4.26×10^{16} sej/year
5	$ECEW_{TP}$	4.9×10^{16} sej/year
	$ECEW_{max}$	4.9×10^{16} sej/year
	Total emergy, considering environmental services to dilute pollutants	$\mathbf{2.385 \times 10^{19}}$

As shown in Figure 4, the total plant's emergy budget for wastewater treatment is driven by the purchased resources consumed (F), 98.29%, and in a small proportion of renewable resources (R), 1.71%. The output emergy flows of the Iași MWWTP are made of the sludge emergy and the ECEW of the sewage system.

In Figure 5, it can be observed that the graphical representation of renewable resources contributed to the total emergy budget. The oxygen demand of the aerobic decomposition phases for bacterial respiration has the most significant contribution to the total emergy budget (1.61%), among renewable resources. At the same time, land occupation plays the dominant role among non-renewable resources.

In Figure 6, the graphical representation of the purchased resources contribution to the total emergy budget may be observed. The electricity consumption of the entire plant is the dominant contributor to the total emergy budget. The second item that has a considerable contribution to the total emergy budget is the consumption of ferric chloride in the chemical stage, followed by human labor requirements. The Iași wastewater treatment system is a large plant, with great responsibilities in wastewater management, and involves 62 employees, who work in three shifts for 24 h a day, 365 days a year

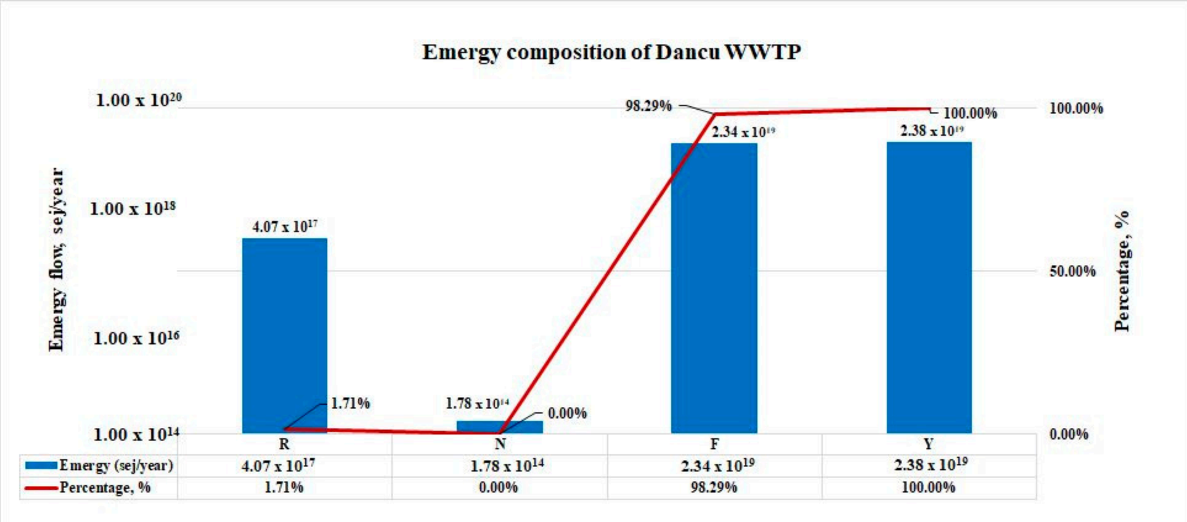

Figure 4. Emergy composition of the Iași MWWTP.

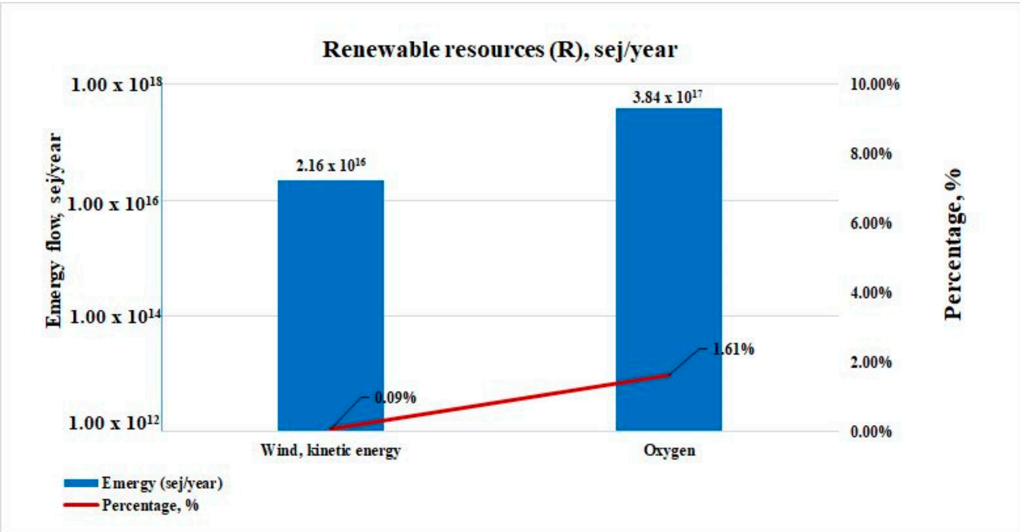

Figure 5. Renewable resources contribution to the total emergy budget (Y).

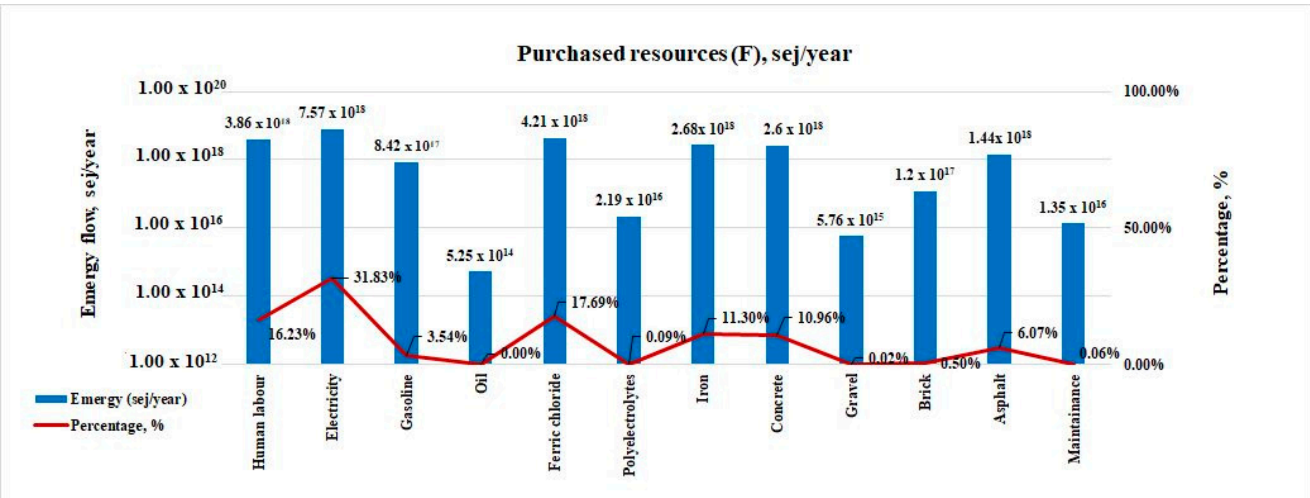

Figure 6. Purchased resources contribution to the total emergy budget (Y).

Significant contributions to the environmental performances of the Iași MWWTP are brought by building materials, for the plant operating phase, and gasoline, to a smaller extent, with ~4% of the total emergy budget. The replacement of these main inputs with less emergy should be considered, e.g., the use of renewable energy sources, such as solar and wind, which have lower UEVs.

The environmental performance of the Iași MWWTP is influenced by the electricity consumption for the aeration of the activated sludge tank and chemical consumption (especially ferric chloride), which generate the most major environmental impacts on the local environment. These results have been confirmed by previous LCA studies [2,11].

The evaluation of the environmental efforts, for assimilating the discharged organic matter load, provided information on the sustainability of the MWWTP. The calculations of ECEW for BOD, COD, TSS, TN, and TP pollutants revealed high emergy values in the effluent. This means that nature's work in assimilating and diluting this load must be taken into account in future analysis. Even if the effluent is within the MAC limits, there is a pollution contribution of the Iași MWWTP to the receiving river, which represents the environmental costs for pollutant dilution and accounts for less than 1% of the total emergy budget.

Regarding the core processes of the MWWTP, two relevant studies were selected for comparing the UEV value of the treated wastewater (5.30×10^{11} sej/m^3) obtained in this study (Table 7). In Romania, no other study applied the EmA, and the studies for comparison were selected based on the treatment process and capacity of the plant. For UEV comparison, the same emergy baseline was adopted, so considering the 12.0×10^{24} sej/yr baseline, 1.30×10^{12} sej/m^3 was corrected to 9.85×10^{11} sej/m^3.

Table 7. Comparison of existing articles on unit emergy values (UEVs).

References	Wastewater Treatment Process	WWTP Capacity m^3/year	UEVs sej/m^3	Emergy Baseline sej/year
This study	Activated sludge + chemical precipitation	44,919,743	5.30×10^{11}	12.0×10^{24}
[43]	Activated sludge	91,250,000	3.40×10^{12}	12.0×10^{24}
[1]	Activated sludge	504,576	1.30×10^{12}	15.83×10^{24}

Based on the emergy calculations, Zhang and Ma [43] obtained the highest UEV, due to the infrastructure emergy input, accounting for at least 92.6% of the entire emergy budget in the treatment plant. Higher UEVs illustrate the worst sustainable level and demonstrate the low efficiency of the MWWTPs. According to Odum [17], high transformity is proportional to a high potential impact, making the treatment process responsible for maintaining a good environmental quality. Considering the environmental services, Giannetti et al. [1] obtained the amount of emergy needed to treat 1 m^3 of wastewater of 9.85×10^{11} sej (UEV corrected). In this study, the UEV (5.30×10^{11} sej/m^3) included infrastructure emergy, operating emergy, and pollutants emergy. Still, the emergy used for treatment in the Iași MWWTP is low, considering the emergy value resulting from the studies mentioned above. A profile of the emergy values, correlated with the WWTP capacity for the last four years, is presented in Table 8, which shows some improvement in 2019 and steady operation afterwards.

Table 8. Evolution of unit emergy values and correlation with wastewater volumes.

Year	Wastewater Volume, m^3	UEV, sej/m^3
2018	40,829,410	5.83×10^{11}
2019	44,919,743	5.30×10^{11}
2020	44,929,511	5.30×10^{11}
2021	43,919,753	5.42×10^{11}

Among the total plant resources needed for wastewater treatment, electricity and reagents consumption have the highest contribution. Replacing these inputs with others that have less emergy would be beneficial for the wastewater treatment's improved efficiency, decreasing the UEVs.

Wastewater is a by-product generated by many different sources (industry, households, agriculture, etc.), which before reaching the plant for treatment is collected, transported, and concentrated through the sewage system. Thus, the performance of the plant is affected by these processes, combined with the high transformity of the treated wastewater (due to the materials and energy content). As already mentioned by other authors, the core value of a wastewater treatment system is to prevent the ecological and human health damage caused by the direct discharge of wastewater; therefore, its yield includes reclaimed water and dewatered sludge [19,20,30,35].

5. Discussion

In this analysis, four indicators have been defined to assist the discussion: the emergy yield ratio (EYR), the environmental loading ratio (ELR), the emergy index of sustainability (ESI), and the renewable emergy percentage (%R) [1]. The indicators, calculated for the examined process (and related equations), are reported in Table 9.

Table 9. Emergy indicators and calculation formulas.

Emergy Indicators			
Emergy Yield Ratio—EYR	(N + R + F)/F = Y/F	1.02	Emergy efficiency and economic
Environment Load Ratio—ELR	(N + F)/R	57.52	Environmental loading exerted by the system
Emergy Sustainable Index—ESI	EYR/ELR	0.02	Sustainability of the system
Renewable ratio—%R	R/Y × 100	1.71%	Sustainability of the system

Emergy-based indicators provide practical information about the quality of inputs and outputs [1], especially the interaction between the system and the environment. Indicators reported in Table 9 identify a low level of environmental sustainability of the wastewater treatment plant managed by SC APAVITAL SA. The extremely high value of environmental load ratio, ELR, suggested that local renewable inputs are insufficient to supply the process demands. The MWWTP should avoid a high ELR status for an extended period, to avoid causing irreversible functional degradation to the environment. Consequently, the lower value of emergy yield ratio, EYR, provided information about the process to intense the exploitation of local resources, whether renewable or not. The resulting sustainability index, ESI, is 0.02, giving information that the system analyzed is not sustainable in the long term. Sustainability requires a high yield and low environmental load, but in this case, the results show the opposite (also, confirmed by a low %R value).

The wastewater management depicted in this study required a large amount of energy and other purchased resources, in contrast with the amount of local renewable resources, such as sun, wind, local biomass production, etc., which was extremely low. There are efforts to decrease the use of electricity in the Iași MWWTP. As the usage of electricity is responsible for the highest emergy contribution to the total emergy budget, a good strategy to reduce the electricity consumption will be necessary. For example, for a reduction of 50%, the total emergy of the system would need to decrease by 10%. Considering the efforts to minimize the use of electricity, the Iași MWWTP has had several experiences to use the energy of biogas, produced by the digestion of sewage sludge.

Electricity consumption generated the largest impact, produced by the Iași MWWTP, on the local environment. These results have been confirmed by previous LCA studies [2,11].

The difference between this study and previous ones is that EmA considers the environmental work needed for generating resources (converted to solar energy), which is the basis for evaluating resources used by the system. In contrast to LCA studies, where this part is not included, here, the environmental impacts are quantified by resources depletion, supporting the system as well as the emissions and wastes released. In this study, the total emergy used by the wastewater treatment processes can be considered an indicator of the environmental impacts, observing that the emergy input associated with the local renewable resources is negligible.

To decrease the use of purchased resources, an optimization of the plant operation and a management analysis would be necessary. Likewise, access to funding to support renewable energy as the supply for wastewater treatment processes would decrease the overall environmental impacts. Finally, this study not only represents a sustainability assessment of a wastewater treatment process but also allows for the identification of the main resources consumption that maintain it and their further allocation.

6. Conclusions

A holistic approach of evaluating both the contribution of nature and society was performed in this study, so as to support water operators to improve wastewater treatment, according to legal requirements and the availability of local resources.

The analysis of a municipal wastewater treatment plant, consisting of mechanical, biological, and tertiary treatment (for nitrogen and phosphorous removal), led to evaluating the emergy costs of wastewater treatment required for nature and society. The wastewater treatment processes demand extensive amounts of purchased resources.

The wastewater treatment process is designed to comply with the limits established by the legal framework for wastewater quality discharged into the river. This means that part of the organic matter carried by wastewater is released into the environment, as an output of the plant. This study presented a preliminary approach to evaluating nature's work in assimilating this load. Considering the fact that nature can assimilate all the organic load from the wastewater discharged, the total emergy required to support microbiological degradation will involve an increased rate of natural fluxes.

To a large extent, the Iași municipal wastewater treatment plant is running, mainly, on purchased inputs, and is using negligible amounts of renewable resources from the local environment. Great efforts are made to reduce the electricity consumption and to replace the source of energy by using renewable energy, such as solar and wind.

Following the application of the EmA to assess the environmental performance of the Iași municipal wastewater treatment system, the following aspects can be depicted:

- Every input in the wastewater treatment processes generates a greater or lesser impact, and the EmA allows to classify these inputs according to their quality, prioritizing actions towards a more sustainable operation;
- The study provided a quantitative overview of the resources used (renewable, non-renewable, and purchased) and may support future studies to value the ecosystems services used by MWWTPs;
- Electricity consumption is the major contributor to the total emergy budget, which allows prioritizing actions towards the replacement of the energy supply by renewable options;
- Reagents cause impacts against surface water quality, among these, ferric chloride is the reagent with the higher contribution on the impact, which implies a need of the environmental efforts for assimilating the discharged organic matter load;
- The values of ECEW for BOD, COD, TSS, TN, and TP pollutants revealed high emergy values in the effluent, and, consequently, nature's work for its dilution;
- Treated wastewater released as an output from the plant provides an impact on the surface water quality, which can further influence the oxygen demand for organic matter decomposition.

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Abbreviations and Symbols

MWWTP	municipal wastewater treatment plant
EmA	emergy analysis
BOD	biochemical oxygen demand
COD	chemical oxygen demand
TSS	total suspended solids
TN	total nitrogen
TP	total phosphorus
EYR	the emergy yield ratio
ELR	the environmental loading ratio
ESI	the emergy index of sustainability
UEV	unit emergy value
NTPA	Romanian technical normative regarding wastewater discharging
MAC	maximum allowed concentrations
RE	removal efficiency
sej	solar emergy joules
J	Joule
g	grams
m^3	cubic meter
yr	year

References

1. Giannetti, B.F.; Silva, C.C.; Agostinho, F.; Almeida, C.M.V.B. Emergy Evaluation of Domestic Wastewater Treatments: The Role of Energy and Materials Consumption and Carbon Emissions. *J. Environ. Account. Manag.* **2013**, *4*, 317–338. [CrossRef]
2. Teodosiu, C.; Bârjoveanu, G.; Robu Slușer, B.; Ene Popa, S.A.; Trofin, O. Environmental assessment of municipal wastewater discharges: A comparative study of evaluation methods. *Int. J. Life Cycle Assess.* **2016**, *21*, 395–411. [CrossRef]
3. Tang, T.; Strokal, M.; van Vliet, M.T.H.; Seuntjens, P.; Burek, P.; Kroeze, C.; Langan, S.; Wada, Y. Bridging global, basin and local-scale water quality modeling towards enhancing water quality management worldwide. *Curr. Opin. Environ. Sustain.* **2019**, *36*, 39–48. [CrossRef]
4. Yaroshenko, I.; Kirsanov, D.; Marjanovic, M.; Lieberzeit, P.A.; Kprpstynska, O.; Mason, A.; Frau, I.; Legin, A. Real-Time Water Quality Monitoring with Chemical Sensors. *Sensors* **2020**, *20*, 3432. [CrossRef]
5. Sambito, M.; Freni, G. Strategies for Improving Optimal Positioning of Quality Sensors in Urban Drainage Systems for Non-Conservative Contaminants. *Water* **2021**, *13*, 934. [CrossRef]
6. Wackernagel, M.; Rees, W.E. *Our Ecological Footprint: Reducing Human Impact on the Earth*; New Society Publishers: Philadelphia, PA, USA, 1996.
7. Vanham, D.; Leip, A.; Galli, A.; Kastner, T.; Bruckner, M.; Uwizeye, A.; van Dijik, K.; Ercin, E.; Dalin, C.; Brandão, M.; et al. Environmental footprint family to address local to planetary sustainability and deliver on the SDGs. *Sci. Total Environ.* **2019**, *693*, 133642. [CrossRef]

8. Grönlund, S.E. Indicators and methods to assess sustainability of wastewater sludge management in the perspective of two systems ecology models. *Ecol. Indic.* **2019**, *100*, 45–54. [CrossRef]
9. Fan, Y.P.; Qiao, Q.; Fang, L.; Yao, Y. Emergy analysis on industrial symbiosis of an industrial park–a case study of Hefei economic and technological development area. *J. Clean. Prod.* **2017**, *141*, 791–798. [CrossRef]
10. Shao, L.; Chen, G.Q. Exergy based renewability assessment: Case study to ecological wastewater treatment. *Ecol. Indic.* **2015**, *58*, 392–401. [CrossRef]
11. Bârjoveanu, G.; Comandaru, I.M.; Rodriguez-Garcia, G.; Hospido, A.; Teodosiu, C. Evaluation of water services system through LCA. A case study for Iași City, Romania. *Int. J. Life Cycle Assess.* **2014**, *19*, 449–462. [CrossRef]
12. Pintilie, L.; Torres, C.M.; Teodosiu, C.; Castells, F. Urban wastewater reclamation for industrial reuse: An LCA case study. *J. Clean. Prod.* **2016**, *139*, 1–14. [CrossRef]
13. Heimersson, A.; Svanström, M.; Ekvall, T. Opportunities of consequential and attributional modeling in life cycle assessment of wastewater and sludge management. *J. Clean. Prod.* **2019**, *222*, 242–251. [CrossRef]
14. Tabesh, M.; Masooleh, M.F.; Roghani, B.; Motevallian, S.S. Life-Cycle Assessment (LCA) of Wastewater Treatment Plants: A Case Study of Tehran, Iran. *Int. J. Civ. Eng.* **2019**, *17*, 1155–1169. [CrossRef]
15. Bârjoveanu, G.; Cojocariu, C.; Robu, B.; Teodosiu, C. Integrated assessment of wastewater treatment plants for sustainable river basin management. *Environ. Eng. Manag. J.* **2010**, *9*, 1251–1258. [CrossRef]
16. Teodosiu, C.; Robu, B.; Cojocariu, C.; Bârjoveanu, G. Environmental impact and risk quantification based on selected water quality indicators. *Nat. Hazards* **2015**, *75*, 89–105. [CrossRef]
17. Odum, H.T. *Environmental Accounting: Emergy and Environmental Decision Making*; John Wiley and Sons: New York, NY, USA, 1996.
18. Shao, S.; Mu, H.; Yang, F.; Zhang, Y.; Li, J. Application of Emergy Analysis to the Sustainability Evaluation of Municipal Wastewater Treatment Plants. *Sustainability* **2016**, *9*, 8. [CrossRef]
19. Arden, S.; Ma, X.; Brown, M.T. Holistic analysis of urban water systems in the Greater Cincinnati region: (2) resource use profiles by emergy accounting approach. *Water Res. X* **2019**, *2*, 100012. [CrossRef]
20. Alizadeh, S.; Zafari-koloukhi, H.; Rostami, F.; Rouhbakhsh, M.; Avami, A. The eco-efficiency assessment of wastewater treatment plants in the city of Mashhad using emergy and life cycle analyses. *J. Clean. Prod.* **2020**, *249*, 119327. [CrossRef]
21. Rugani, B.; Benetto, E. Improvements to emergy evaluations by using life cycle assessment. *Environ. Sci. Technol.* **2012**, *46*, 4701–4712. [CrossRef]
22. Su, Y.; He, S.; Wang, K.; Shahtahmassebi, A.R.; Zhang, L.; Zhang, J.; Zhang, M.; Gan, M. Quantifying the sustainability of three types of agricultural production in China: An emergy analysis with the integration of environmental pollution. *J. Clean. Prod.* **2020**, *252*, 119650. [CrossRef]
23. Zhao, G.; Zhang, H.; Zhang, G.J.; Guo, L.M. Morphology and coupling of environmental boundaries in an iron and steel industrial system for modelling metabolic behaviours of mass and energy. *J. Clean. Prod.* **2015**, *100*, 247–261. [CrossRef]
24. Pan, H.Y.; Zhang, X.; Wu, J.; Zhang, Y.; Lin, L.; Yang, G.; Deng, S.; Li, L.; Yu, X.; Qi, H.; et al. Sustainability evaluation of a steel production system in China based on emergy. *J. Clean. Prod.* **2016**, *112*, 1498–1509. [CrossRef]
25. Liu, G.Y.; Yang, Z.F.; Chen, B.; Ulgiati, S. Emergy-based dynamic mechanisms of urban development, resource consumption and environmental impacts. *Ecol. Model.* **2014**, *271*, 90–102. [CrossRef]
26. Yang, Q.; Chen, G.Q.; Liao, S.; Zhao, Y.H.; Peng, H.P. Environmental sustainability of wind power: An emergy analysis of a Chinese wind farm. *Renew. Sustain. Energy Rev.* **2013**, *25*, 229–239. [CrossRef]
27. Puca, A.; Carrano, M.; Liu, G.; Musella, D.; Ripa, M.; Viglia, S.; Ulgiati, S. Energy and eMergy assessment of the production and operation of a personal computer. *Resour. Conserv. Recycl.* **2017**, *116*, 124–136. [CrossRef]
28. Wang, Y.; Zhang, X.; Liao, W.; Wu, J.; Yang, Z.; Shui, W.; Deng, S.; Zhang, Y.; Lin, L.; Xiao, Y.; et al. Investigating impact of waste reuse on the sustainability of municipal solid waste (MSW) incineration industry using emergy approach: A case study from Sichuan province, China. *Waste Manag.* **2018**, *77*, 252–267. [CrossRef]
29. Grönlund, S.E.; Billgren, C.; Tonderski, K.S.; Raburu, P.O. Emergy assessment of a wastewater treatment pond system in the Lake Victoria Basin. *J. Environ. Account. Manag.* **2017**, *5*, 11–26. [CrossRef]
30. Vassalo, P.; Paoli, C.; Fabiano, M. Emergy required for the complete treatment of municipal wastewater. *Ecol. Eng.* **2009**, *35*, 687–694. [CrossRef]
31. Siracusa, G.; La Rosa, A.D. Design of a constructed wetland for wastewater treatment in a Sicilian town and environmental evaluation using the emergy analysis. *Ecol. Model.* **2006**, *197*, 490–497. [CrossRef]
32. Cano Londoño, N.A.C.; Suarez, A.G.; Velasquez, H.I.; Ruiz-Mercado, G.J. Emergy analysis for the sustainable utilization of biosolids generated in a municipal wastewater treatment plant. *J. Clean. Prod.* **2017**, *141*, 182–193. [CrossRef]
33. Zhang, X.; Deng, S.; Wu, J.; Jiang, W. A sustainability analysis of a municipal sewage treatment ecosystem based on emergy. *Ecol. Eng.* **2010**, *36*, 685–696. [CrossRef]
34. Fonseca, C.R.; Diaz-Delgado, C.; Esteller, M.V.; Garcia-Pulido, D. Geoinformatics tool with an emergy accounting approach for evaluating the sustainability of water systems: Case study of the Lerma river, Mexico. *Ecol. Eng.* **2017**, *99*, 436–453. [CrossRef]
35. Björklund, J.; Geber, U.; Rydberg, T. Emergy analysis of municipal wastewater treatment and generation of electricity by digestion of sewage sludge. *Resour. Conserv. Recycl.* **2001**, *31*, 293–316. [CrossRef]
36. Geber, U.; Björklund, J. The relationship between ecosystem services and purchased input in Swedish wastewater treatment systems—A case study. *Ecol. Eng.* **2002**, *19*, 97–117. [CrossRef]

37. Yang, L.; Kong, F.-L.; Xi, M.; Li, Y.; Wang, S. Environmental economic value calculation and sustainability assessment for constructed rapid infiltration system based on emergy analysis. *J. Clean. Prod.* **2017**, *167*, 582–588. [CrossRef]
38. Brown, M.T.; Campbell, D.E.; De Vilbiss, C.; Ulgiati, S. The geobiosphere emergy baseline: A synthesis. *Ecol. Model.* **2016**, *339*, 92–95. [CrossRef]
39. He, S.; Zhu, D.; Chen, Y.; Liu, X.; Chen, Y.; Wang, X. Application and problems of emergy evaluation: A systemic review based on bibliometric and content analysis methods. *Ecol. Indic.* **2020**, *114*, 106304. [CrossRef]
40. *Romanian Government Decision no. 188 of February 2002 Ammended and Supplemented by the Government Decisions no. 352/2005 and 210/2007 for the Approval of the Legal Norms Regarding the Conditions for Discharging Wastewater into the Aquatic ENVIRONMENT (transposing Directive 91/271/EEC of 21 May 1991 Concerning Urban Wastewater Treatment, Modified and Completed by Directive 98/15/EC, 27 February 1998)*; Romanian Government: Bucharest, Romania, 2007.
41. APAVITAL. *Water and Sewerage Public Services Regional Operator*; Activity Report; APAVITAL: Iași, Romania, 2018.
42. Prăjanu, C.C.; Toma, D.; Vîrlan, C.M.; Marcoie, N. Studies Related to the Biological Treatment of Wastewater within the Wastewater Treatment Plant of Iași City. *Sciendo* **2018**, *20*, 57–64. [CrossRef]
43. Zhang, J.; Ma, L. Environmental Sustainability Assessment of a New Sewage Treatment Plant in China Based on Infrastructure Construction and Operation Phases Emergy Analysis. *Water* **2020**, *12*, 484. [CrossRef]
44. Ulgiati, S.; Brown, M.T. Emergy evaluations and environmental loading of electricity production systems. *J. Clean. Prod.* **2002**, *10*, 321–334.
45. The Climate Data Factory. Available online: https://shop.theclimatedatafactory.com/ (accessed on 17 June 2020).
46. World Weather Online. Available online: https://www.worldweatheronline.com/ (accessed on 17 June 2020).